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Systematic Review

Effect of Plasma Treatment on Root Canal Sealers' Adhesion to Intraradicular Dentin—A Systematic Review

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Abstract: This investigation aimed to assess, through a systematic review, the effect of non-thermal plasma treatments on root canal sealers' adhesion to dentin. This study followed the 2020 Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. A literature search was undertaken without limits on time or language, until May 2023, in PubMed–MEDLINE, Scopus, Web of Science, OpenGrey, and three endodontic journals. The included studies underwent quality assessment and data extraction. Out of an initial 188 articles, 4 studies were included. Three of these studies based the adhesion ability on the push-out test in human extracted teeth, while the other used bovine dentin samples to measure the contact angle with the sealer (wettability). While there was no consensus about the effect of non-thermal plasma (NTP) on the AH Plus sealer's adhesion to radicular dentin, NTP seemed to positively influence the adhesion ability of BioRoot RCS and Endosequence BC. The findings of the present review should be interpreted cautiously due to the scarcity of studies on the topic. The NTP parameters should be optimized to obtain a stronger evidence base in endodontics on its role as an adjuvant tool to increase sealers' adhesion to dentin.

Keywords: adhesion; gutta-percha; plasma treatments; root canal filling; root canal obturation; root canal therapy; root canal sealers

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1. Introduction

Endodontic therapy, generally focused on root canal treatment, has a major goal directed to the cure or prevention of periradicular periodontitis. Orthograde endodontic treatment includes cleaning and shaping of the root canal system, preparing it for the subsequent filling, with the aim of maintaining disinfection and preventing reinfection. The latter is achieved by a core—most often gutta-percha—and an endodontic sealer, under well-defined criteria of length and density. The treatment is completed by an adequate coronal restoration [1].

A dentin sealer's adhesion is its ability to adhere to the root canal's walls and promote the union of the filling materials to dentin. Different sealers and filling techniques (e.g., single cone, lateral compaction, or thermoplastic obturation) have been reported to produce an impact in the penetration of the sealer into dentinal tubules, thereby influencing dentin sealers' adhesion [2]. Optimal adhesion of the root filling to the intraradicular dentin leads to fewer gap-containing regions, which would allow fluid infiltration within either sealer–dentin or sealer–core–filling material interfaces [3]. Consequently, it also avoids sealer dislodgment during operative procedures, increasing endodontic treatment success rates [3]. It is widely accepted that sealing ability is of utmost importance to successful outcomes of root canal treatments [3].

A great variety of endodontic sealers are available commercially. They are divided into different groups according to their chemical composition, properties, or therapeutic additives, which influence their performance [4]. Studies have also shown that the sealers' bond strength to dentin may be affected by the pretreatment of canal walls and the type of sealer used [5].

The physicochemical properties of sealers interfere with their ability to adhere to dentin [6]. The epoxy-resin-based sealer AH Plus (Dentsply DeTrey GmbH, Konstanz, Germany) is the gold-standard sealer due to its extensively studied physical properties, such as its high bond strength to dentin [6]. This advantage has been justified by epoxy-resin-based sealers' chemical bonding to exposed collagen and their great capacity to form smooth and compact tags inside dentinal tubules [6,7]. MTA Fillapex is composed of a salicylate–resin matrix filled with MTA, natural resin, bismuth oxide, and silica [8]. This sealer's composition is primarily resin, which raises doubts concerning its classification as a true calcium-silicate-based sealer or MTA-based sealer [4]. Nevertheless, it is reported that the set sealer releases calcium and hydroxyl ions. When the material comes into contact with phosphate-containing fluids, these ions cause the formation of apatite, which may deposit within collagen fibrils, promoting controlled mineral nucleation on dentin, seen as the formation of an interfacial layer with tag-like structures [7,8]. MTA Fillapex's low bond strength could be due to the low adhesion capacity of these tag-like structures [9].

Calcium-silicate-based sealers, such as BioRoot RCS and Endosequence BC, have become popular in endodontics, mainly due to their biocompatibility and bioactivity [10]. These sealers have the potential to adhere chemically to dentin through the production of hydroxyapatite during setting [6]. Although they have undergone great development to improve their performance, there is still a lack of consensus regarding their bond strength to intraradicular dentin [6,11].

Plasma, considered to be the fourth state of matter, is an electrically conductive medium that responds to electric and magnetic fields and is also a source of large quantities of highly reactive species such as electrons, ions, electronically excited neutrons, and free radicals [12]. Plasmas are generally classified as thermal and non-thermal (or cold plasma), based on the relative temperatures and energy of the different plasma species (electrons, ions, and neutrons) [12]. In thermal plasmas, electrons and heavy particles are in thermal equilibrium, while in non-thermal plasma (NTP), electrons are hotter than ions and neutrons are at room temperature [12]. NTP can be used under vacuum or atmospheric conditions, using inert gases like argon (Ar) or helium (He), reactive gases such as oxygen (O_2) or nitrogen (N_2), or a mixture of two or more gases [13,14]. Plasma treatments provide an effective and clean technology for surface activation without changing the materials' original structure and functional properties [15]. Previous studies have shown that NTP is efficient for cleaning/decontaminating and sterilizing instruments [16] and tooth whitening [17], and it seems to be a promising tool in combating dental biofilms [18]. Moreover, this technology has been shown to increase the wettability and hydrophilicity of different surfaces, such as dentin, enamel, and composites, improving their adhesive features or etching dentinal tubules, ensuring higher mechanical retention of root canal sealers [19].

To the best of our knowledge, to date, no systematic review has evaluated the influence of NTP on the adhesion between endodontic sealers and intraradicular dentin. Thus, this work aimed to assess, through a systematic review, the effect of NTP treatments on root canal sealers' adhesion to dentin.

2. Materials and Methods

This systematic review followed the recommendations of the 2020 Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [20].

2.1. Eligibility Criteria

This study was conducted to answer the PICO question "Does the NTP treatment affect sealers' adhesion to dentin compared to no treatment?", with the following parameters: extracted teeth as the participants, plasma treatment as the intervention, no treatment as the comparison, and evaluating root canal sealers' adhesion to dentin as the outcome.

Only in vitro studies that treated dentin with plasma technology and assessed the effects of NTP treatments on root canal sealers' adhesion to dentin were included. Studies that did not use a control group (without plasma treatment) were excluded.

2.2. Search Strategy

The search was carried out in May 2023 on PubMed (Medline), Scopus, and Web of Science. The electronic search combined Medical Subject Heading (MeSH) terms, text words (tw), and truncation terms. The Boolean operators "AND" and "OR" were used to create the search strategy (Table 1). No language or publication date restrictions were applied. Additionally, gray literature was investigated through OpenGrey, and a manual search of the *Journal of Endodontics*, *International Endodontic Journal*, and *Australian Endodontic Journal* was performed to find any additional papers. Moreover, an additional search was conducted using the reference lists of all included papers. References from different databases were imported into the EndNote X9 software (Thomson Reuters, New York, NY, USA), which automatically removed duplicate records.

Table 1. Search strategy in different databases.

Database	Search Strategy	Findings
PubMed	#1 ((non-thermal plasma[Title/Abstract]) or (nonthermal plasma[Title/Abstract]) or (Plasma Gases[Title/Abstract]) or (plasma treatment[Title/Abstract]) or plasma[Title/Abstract] or (Plasma Gases[MeSH Terms]) or plasma[MeSH Terms])	
	#2 ((dental cements[MeSH Terms]) or (root canal sealants[MeSH Terms]) or (dental cement *[Title/Abstract]) or (root canal seal *[Title/Abstract]) or (endodontic seal *[Title/Abstract]) or (root canal fill *[Title/Abstract]) or (seal*[Title/Abstract]))	
	#3 ((endodontic *[Title/Abstract]) or (root canal[Title/Abstract]) or (endodontic treatment[Title/Abstract]) or (root canal treatment[Title/Abstract]) or (Root Canal Therapy[Title/Abstract]) or (Root Canal Therapy[MeSH Terms]) or (Endodontics[MeSH Terms])	
	#1 and #2 and #3	96
Scopus	#1 TITLE-ABS-KEY("non-thermal plasma" or "nonthermal plasma" or "Plasma Gases" or "plasma treatment" or plasma)	
	#2 TITLE-ABS-KEY("dental cements" or "root canal sealants" or "dental cement *" or "root canal seal *" or "endodontic seal *" or "root canal fill *" or "seal *")	
	#3 TITLE-ABS-KEY("endodontic *" or "root canal" or "endodontic treatment" or "root canal treatment" or "Root Canal Therapy")	
	#1 and #2 and #3	140
Web of Science	#1 TS = ("non-thermal plasma" or "nonthermal plasma" or "Plasma Gases" or "plasma treatment" or plasma)	
	#2 TS = ("dental cements" or "root canal sealants" or "dental cement *" or "root canal seal*" or "endodontic seal *" OR "root canal fill *" or "seal *")	
	#3 TS = ("endodontic *" or "root canal" or "endodontic treatment" or "root canal treatment" or "Root Canal Therapy")	
	#1 and #2 and #3	83

2.3. Selection of the Studies

Two reviewers independently assessed the searched titles and abstracts and discarded the non-eligible papers. When the title and abstract were insufficient to confirm or exclude a particular study, they read the full text. In case of divergence, a third author decided whether the paper should be included.

2.4. Data Extraction

The following information was extracted and recorded from each included study: tooth type, non-thermal treatment (i.e., gas/application time, plasma mode, device used, distance, pressure, and power applied), methodology for testing adhesion ability (push-out testing parameters (i.e., filling materials used, storage, canal segments analyzed, slice thickness, plunger diameter, and plunger loading direction) and contact angle analysis), and main results.

2.5. Risk-of-Bias Assessment

Two authors independently evaluated the risk of bias in each selected study. The risk of bias assessment method was adapted from a previously published systematic review [21]. The following parameters were considered: (1) randomization, (2) blinding, (3) standardization of specimen selection, (4) standardized preparation (single operator), and (5) reporting of data. If the above parameters were mentioned, the risk of bias was recorded as low; if the parameters were not mentioned, it was recorded as high; if their mention was not clear, it was recorded as unclear. Disagreements among authors were resolved through discussion with a third author.

3. Results

Figure 1 shows the flow diagram of the search strategy. After duplicates were removed, the search generated 188 studies. After the analysis of titles and abstracts, five were selected. After comprehensive reading of these studies, one was excluded due to not treating dentin with plasma technology [22]. Therefore, four studies fulfilled the eligibility criteria and were included in this systematic review.

Table 2 shows the results of the included papers' risk of bias. All studies had a high risk of bias with respect to blinding, randomization process, and standardized sample preparation (single operator), because these parameters were not mentioned. All of the studies reported all results and performed sample standardization, so they were considered to have a low risk of bias in these parameters. None of the included studies had a low risk of bias in all parameters evaluated, so the overall risk of bias of the selected studies was high. Table 3 summarizes the included studies.

Table 2. Quality assessment of the included studies [13,23–25].

Author (Year)	Randomization	Blinding	Standardization of Sample Selection	Standardization Preparation (Single Operator)	Reporting of Data
Prado et al., 2016	High	High	Low	High	Low
Menezes et al., 2017	High	High	Low	High	Low
Yeter et al., 2020	High	High	Low	High	Low
Garlapati et al., 2021	High	High	Low	High	Low

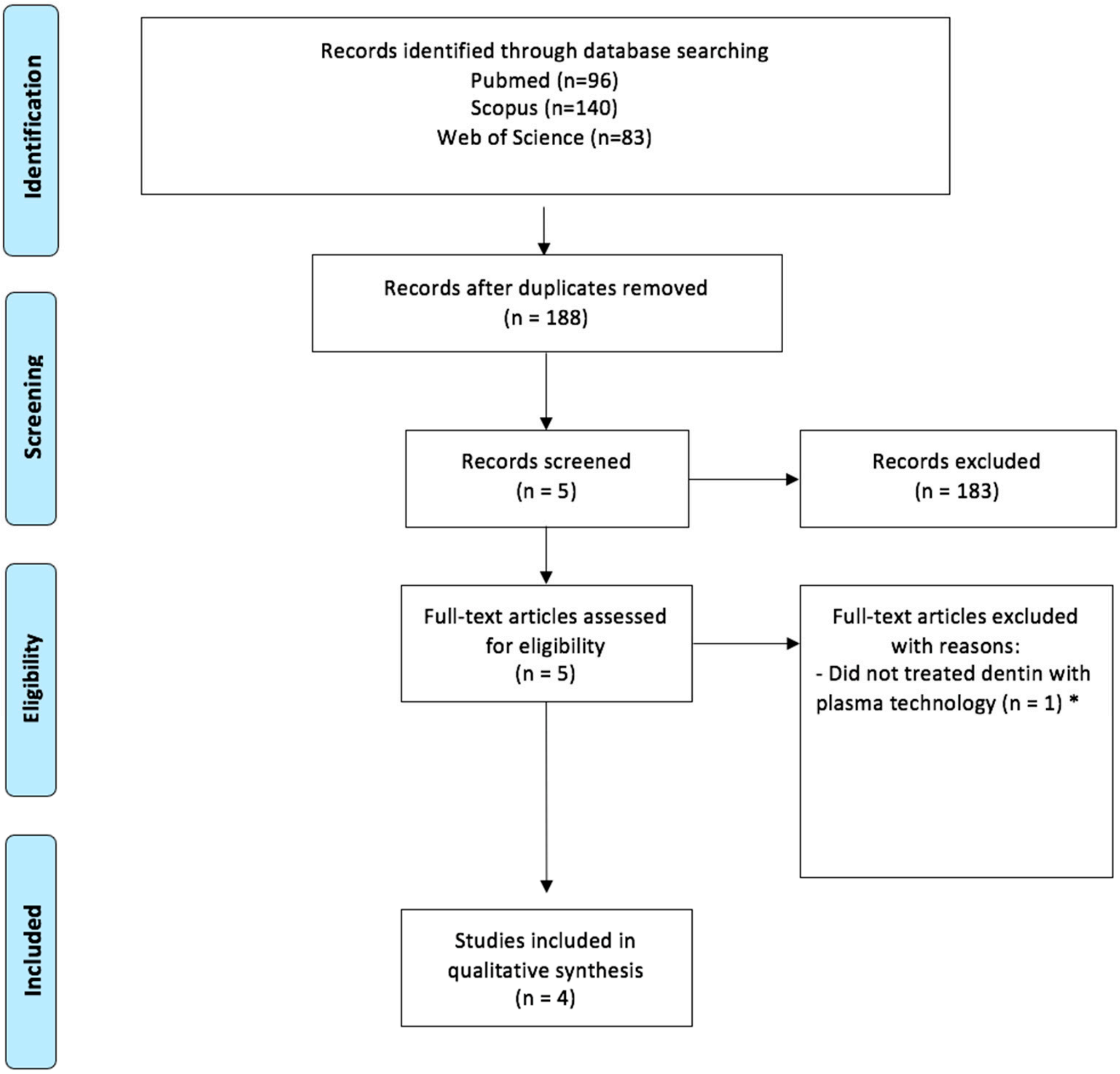

Figure 1. Flow diagram of the search strategy. * Record excluded [22].

3.1. NTP Treatment Methodology

Three studies used human single-rooted extracted teeth [23–25]. Only one used bovine teeth [13]. Prado, et al. [13] and Garlapati, et al. [25] applied NTP treatments under vacuum conditions using a glass reactor, while Yeter, et al. [23] and Menezes, et al. [24] used an atmospheric-pressure plasma jet. Under vacuum conditions, a power of 60 W was applied to generate the plasma, with a working pressure of 10 Pa and a base pressure of 2 Pa. For plasma application through a plasma jet mode, the gas pressure was kept at 6 bar and 2.5 bar; the distance between the tip of the plasma jet and the dentin was approximately 5 mm. Two studies used argon plasma [13,23], while the other two applied a mixture of gases [24,25]. The application time was 30 s, except in the study of Menezes, et al. [24], where it was 1 min.

Table 3. Characteristics of the included studies (GP: gutta-percha; Ar: argon; O_2: oxygen; He: helium; P: pressure; SFE: surface free energy, SE: sealer wettability) [13,23–25].

Author	Tooth Type	Non-Thermal Treatment						Methodology for Testing Dentin-Sealer Adhesion Capacity								Main Results
								Bond Strength Analysis—Push-Out Test							Contact Angle Analysis	
		Gas	Plasma Mode	Application Time	Distance	Power	Pressure	Filling Material	Storage and Duration	Canal Segments	Slice Thickness	Plunger Diameter	Crosshead Speed	Plunger Loading Direction		
Prado et al., 2016	Bovine incisors	Argon	Vacuum	30 s	-	60 W	$P_{\text{base}} = 2$ Pa $P_{\text{work}} = 10$ Pa	AH Plus	-	-	-	-	-	-	Wettability—contact angle between the dentin and the AH Plus sealer	Argon plasma increased the wettability of AH Plus, favoring its bonding to dentin
Menezes et al., 2017	Human single-rooted premolars	Mixture of 98% He and 2% O_2	Jet	1 min	5 mm	-	6 bars	GP + AH Plus GP + MTA Fillapex	100% humidity for 2 days	Coronal; middle; apical	1 mm	0.76 mm coronal; 0.60 mm middle; 0.40 mm apical	0.5 mm/min	Unclear	-	Regarding AH Plus, bond strength was similar in the plasma and control groups. For MTA Fillapex, the bond strength decreased with plasma treatment
Yeter et al., 2020	Human single-rooted mandibular premolars	Argon	Jet	30 s	5 mm	-	2.5 bars	GP + AH Plus GP + Endosequence BC	100% humidity for 7 days	Coronal; middle	Unclear	Unclear	0.5 mm/min	Apical–coronal	-	Argon plasma did not influence the bond strength of AH Plus to dentin. The Endosequence BC showed a better bond strength than the AH Plus after argon plasma treatment
Garlapati et al., 2021	Human single-rooted mandibular premolar	Mixture of He and Ar	Vacuum	30 s	-	60 W	$P_{\text{base}} = 2$ Pa $P_{\text{work}} = 10$ Pa	GP + AH Plus GP + BioRoot RCS	Not mentioned	Middle	2 mm	1 mm	1 mm/min	Unclear	-	Plasma treatment enhanced the bond strength of BioRoot RCS and AH Plus

3.2. Dentin Sealers' Adhesion Assessment

- Push-out test [23–25]
    - (a) Filling material and sample storage: Three studies filled the canal with gutta-percha and sealer [23–25]. The storage time ranged from 2 to 7 days, and the specimens were kept in an incubator at 37 °C and 100% humidity. Garlapati, et al. [25] did not mention the storage conditions and time.
    - (b) Slice thickness and canal segments: The thickness of the slices varied between 1 and 2 mm. Yeter, et al. [23] did not clearly describe the slice thickness. Menezes, et al. [24] used apical, middle, and coronal thirds, Garlapati, et al. [25] used only the middle third, and Yeter, et al. [23] used the coronal and middle thirds.
    - (c) Plunger diameter, speed, and direction: Menezes, et al. [24] used three plunger sizes to equal the diameter of each root third, Garlapati, et al. [25] used a plunger of 1 mm, and Yeter, et al. [23] did not mention the plunger diameter used. The plunger's loading direction was unclear in two studies. Yeter, et al. [23] applied an apical–coronal direction. The crosshead speed varied between 0.5 mm/min and 1 mm/min.
- Contact angle analysis [13].

In one of the studies, adhesion was assessed based on the wettability of the resin-based sealer AH Plus. It was calculated through the contact angle between the dentin surfaces and the sealer [13].

3.3. Influence of NTP on Dentin Sealers' Adhesion

The epoxy-resin-based sealer AH Plus was tested in all of the included studies. The other sealers tested were MTA Fillapex [24], BioRoot RCS [25], and Endosequence BC [23]. In two studies, plasma treatment did not influence the bond strength of AH Plus to dentin [23,24]. On the other hand, Garlapati, et al. [25] and Prado, et al. [13] concluded that plasma treatment improved the AH Plus–dentin adhesion. The bond strength of BioRoot RCS and Endosequence BC was positively influenced by plasma treatment. For MTA Fillapex, the bond strength decreased with plasma treatment.

4. Discussion

Root canal filling materials' adhesion to dentin has been widely tested using the push-out bond strength (POBS) test, also called dislodgement resistance [26]. Well-controlled experiments are challenging when using biological samples, due to the substantial effects of the inherent biological, physical, and chemical variances imposed by natural samples. A recent study investigated the reliability of using bovine teeth as an alternative to human teeth for testing the POBS of sealers to dentin and concluded that the dentin substrate did not influence the sealers' bond strength [27]. Only one of the studies included in our review used bovine teeth [13]. The variations in push-out methodology are a concern because they prevent the comparison of results from different researchers [26]. Generally, studies have followed two philosophies: the root canals are either filled with the sealer alone or combined with gutta-percha with the filling techniques of cold lateral compaction, single-cone filling, or specific obturation systems such as Resilon/Epiphany [28,29]. Three studies included in this review filled the samples with gutta-percha and sealer [23–25]. According to some authors, filling the canals only with sealer ensures that there are no confounding factors and that the adhesion strength tested is that of the sealer [28].

The adhesion processes are mostly influenced by the relative surface free energy, which determines the predisposition of the material's surface for establishing new interactions/bonds with the surrounding medium. In the same way, wettability is influenced by the interfacial tensions and, in turn, by the surface free energy [30]. Thus, contact angle evaluation has been widely used to measure the surface wettability of different materials [22]. The contact angle has an inverse relationship with the surface free energy (wettability), i.e., the lower the contact angle, the greater the surface free energy and, hence, likely greater adhesion [13]. Prado, et al. [13] observed increased surface free energy, correlated with the higher wettability of bovine dentin with AH Plus after 30 s of argon NTP, compared to the control (i.e., without NTP). They also reported a chemical change based on FTIR results. Argon plasma treatment reduced the organic compounds of dentin (amide I and II bands) and increased the inorganic component (the carbonade band), due to its ability to etch dentin surfaces; no associated topographical changes occurred. Based on these findings, the authors concluded that argon treatment favored the bonding of the sealer to dentin surfaces [13]. However, only the resinous AH Plus sealer was evaluated.

There is no consensus or sufficient data about NTP's effect on radicular dentin in terms of endodontic sealers' adhesion. In the present investigation, a systematic review was conducted to answer the following PICO question: Does the NTP treatment affect sealers' adhesion to dentin compared to no treatment? A few ex-vivo studies met the selection criteria, even though some disparity in the materials and methodologies was registered, which prevented a meta-analysis from being performed. Our findings indicate that NTP on dentin root walls might positively impact sealers' adhesion, considering the increased POBS or surface energy and wettability values reported in the selected literature.

The bioceramic sealer (BioRoot RCS) showed the highest POBS values, followed by the epoxy-resin-based sealer (AH Plus), after mixing helium and argon atmospheres on dentin surfaces [25]. Moreover, the NTP dentin groups showed an increase in bond strength more than two times higher than the non-plasma-treated dentin (control groups), independent of the sealer [25]. The better bond strength of the bioceramic sealer after NTP, compared to the resinous AH Plus [25], was also corroborated by other authors who stressed its good performance, particularly in the middle region of the root canal [23]. Albeit with different plasma applications, both studies included two recently developed calcium-silicate-based sealers: BioRoot RCS [25] and Endosequence [23], reported to have adhesive characteristics and bioactivity. A recent review of current sealers points out that tricalcium silicate sealers are associated with the lowest relative microleakage compared to the standard AH Plus [4]. The higher POBS values obtained can derive from the chemical nature of bioceramic sealers, affecting properties such as fluidity, their easy spread over the dentin walls due to their low contact angle, or an increase in dentin wettability after NTP [15,23,31]. It was reported that the dentin surface modification after NTP, such as enhanced wettability and chemical interaction, could favor dentinal tubule penetration and the bioceramic sealer's bond strength [23]. Although the authors did not explain the minor influence of NTP on the POBS evaluation of AH Plus [23], other factors, such as the chemical and structural alterations that different irrigating solutions can produce in dentin surfaces, might have affected the results [32].

There are other endodontic procedures aimed to open plasma treatments that can be created under low pressure or atmospheric pressure and increase wettability, such as the standard chelating agent EDTA [33]. However, the additional NTP generally increased these properties, acting as an adjuvant procedure, as shown by the higher POBS values or wettability observed after EDTA exposure [13,25]. Conversely, in the study of Yeter, et al. [23], the final flush was performed with NaOCl. NaOCl may have caused a deproteinization, causing a hydrophilic surface that did not favor the resinous sealer's hydrophilicity [32]. With a similar irrigating solution sequence (EDTA followed by NaOCl), Menezes, et al. [24] found similar bonding values to the control for the NTP groups with either AH Plus or MTA Fillapex. The type of sealer might also have influenced the results.

NTP has been reported to reach deep into the dentinal tubules, similar to or further than bacteria, creating reactive oxygen species and damaging the remaining microorganisms, in addition to cleaning/etching [19]. Thus, it seems to ensure higher mechanical retention and adhesion. This rationale was corroborated by Menezes, et al. [24], Prado, et al. [13], and Garlapati, et al. [25], who reported improved adhesion of NTP surfaces.

Plasma treatments can be carried out at low pressure or atmospheric pressure. The main difference lies in the pressure at which they operate, which affects the plasma density, confinement, and particle behavior [34]. Low-pressure plasmas are generated and sustained in a vacuum or low-pressure environment using vacuum chambers. The benefit of low-pressure plasmas is that the mean free path of the particles (i.e., atoms, ions, and electrons) is relatively long, meaning that they can travel greater distances between collisions. The conditions are much more controllable and reproducible compared to atmospheric-pressure conditions (typically close to 1 atmosphere, where the particles' mean free path is much shorter than in low-pressure plasmas due to the higher gas density), which could compensate (at least partially) for the practical drawbacks of using low-pressure plasma—especially the need for expensive vacuum equipment [35,36]. On the other hand, atmospheric-pressure plasmas have become very attractive because they are generated in an open environment and can be easily implemented [37]. Nevertheless, if particular precautions are not taken, they tend to become thermal, i.e., hot plasmas that can damage heat-sensitive materials or burn living tissues [38]. In the included studies, Prado, et al. [13] and Garlapati, et al. [25] applied NTP treatments under vacuum conditions using a glass reactor, while Yeter, et al. [23] and Menezes, et al. [24] used an atmospheric-pressure plasma jet.

Using low-pressure plasma in dental applications offers several advantages, such as enhanced control over the plasma parameters (e.g., gas composition, pressure, and power), deeper penetration into complex dental structures, access to confined spaces, and uniform treatments due to the better diffusion of the reactive species [22,39–41]. Furthermore, the reduced heat and controlled plasma conditions make low-pressure plasma treatments suitable for treating delicate dental components, such as resin-based composites, polymer-based materials, or dental implants [22,39–41]. However, the potential drawbacks of plasma treatments must be carefully considered. Excessive exposure or high-energy plasma can damage the dentin structure, limiting the treatment's effectiveness and durability. Moreover, implementing plasma treatments requires specialized equipment and expertise, which can increase the cost and complexity of dental procedures. Despite these considerations, plasma treatments offer advantages such as enhanced bonding, improved biocompatibility, effective sterilization, and reduced dentin hypersensitivity [34]. Dental professionals should understand the potential benefits and challenges so as to make informed decisions about incorporating plasma treatments into their practice.

Plasma treatments offer a promising avenue for enhancing dentin surfaces, and the choice of gas composition (e.g., low-pressure processes) plays a crucial role in determining the treatment outcomes [42]. Gas mixing can lead to synergistic effects, creating chemical reactions or interactions that are more effective than using each gas individually [43]. Also, mixing gases expands the range of possible low-pressure plasma treatments and allows for selective treatments [43]. One common gas mixture used in low-pressure plasma treatments is argon (Ar) and oxygen (O_2), which provides several benefits [43]. Ar, like helium (He), is an inert gas with low thermal conductivity, which helps minimize the thermal effects on dentin during plasma treatment. It also acts as a carrier gas, facilitating the transport and interaction of reactive species within the plasma [42]. Oxygen, on the other hand, introduces additional reactive species, enabling more effective cleaning, surface modification, or chemical reactions with the dentin surface [42]. The Ar + O_2 or He + O_2 combination is also an effective sterilization method [18]. The reactive species generated in plasma, such as oxygen radicals, have antimicrobial properties, enabling them to eliminate bacteria, viruses, and other pathogens [18]. This sterilization capability is particularly valuable in infection control during dental procedures, reducing the risk of post-treatment infections [18]. If gases are carefully selected and mixed, the plasma parameters can be controlled, allowing for fine-tuning of the treatment process. Thus, dental professionals can optimize the treatment conditions, ensuring efficient and effective results while minimizing potential risks and adverse effects.

Compared to untreated dentin, i.e., not subjected to plasma treatment, the studies included in this systematic review suggest—albeit with low-certainty evidence—that plasma treatment may be a promising tool for improving the adhesion of endodontic sealers to dentin. Some of the parameters used, such as the time of NTP application, were based on investigations of dental composites' adhesion, because there are insufficient data on root canal dentin–sealer adhesion [14,23]. The type of plasma atmosphere, exposure time, and assessment tools might need to be unified to optimize NTP. However, its high cost has been highlighted.

The findings of the present review should be interpreted cautiously, due to the scarcity of studies on the topic. Moreover, a quantitative analysis was not feasible due to the heterogeneity of the study designs in terms of the plasma treatment (i.e., type of devices used; plasma parameters like power, frequency, gas type, and application time), adhesion methodology, and type of sealers used. Although a total of 188 studies were obtained from the electronic search, only 4 were included after applying the eligibility criteria. Nonetheless, the overall risk of bias of the included studies was high. However, the strict selection of the studies enabled an overview of this contemporary topic, highlighting its potential.

5. Conclusions

The studies included in this systematic review suggest that plasma treatment may be a promising tool for improving endodontic sealers' adhesion to dentin. There is a need to optimize NTP's parameters to develop a stronger evidence base in endodontics on its role as an adjuvant tool to increase sealers' adhesion to dentin. This optimization could help improve the outcomes of root canal treatments.

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